High intensity laser hybrid guiding for electron acceleration

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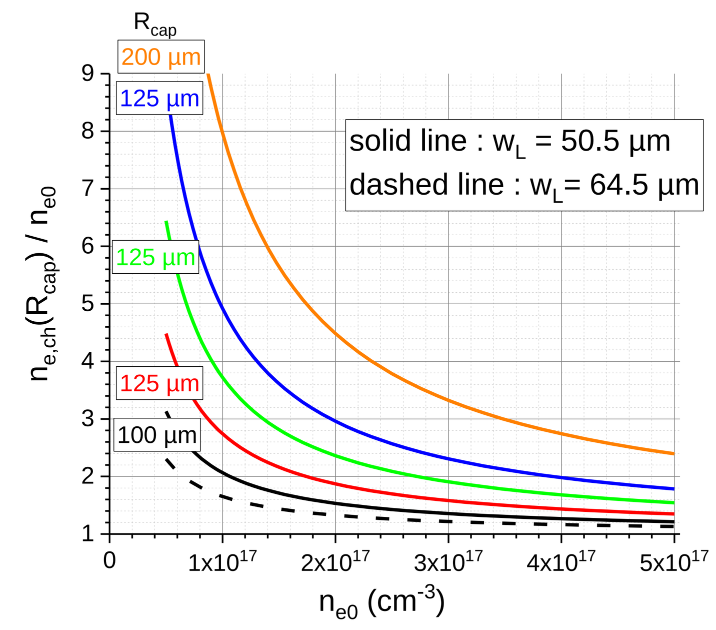
Objective: To control the guiding of a high intensity laser pulse over large distances ($L > 10Z_R$) in a Laser Plasma Accelerator (LPA) stage. An hybrid scheme of guiding is studied that combines a parabolic plasma channel with reflections inside a capillary tube. This scheme can yield an efficient guiding at low plasma densities with a small capillary radius. It requires less energy to create the plasma channel, generating less damage at the capillary walls and facilitating the way to operate at high frequencies. We present results of simulations performed with the WAKE-EP code of plasma generation and laser plasma acceleration up to 1 GeV inside a capillary tube of an electron beam injected at 150 MeV.



Ratio of the density at the capillary wall with the density on axis for various capillary radius R_{cap} and laser waist w_L, as given by the plasma channel best matched guiding condition. Lower values of R_{cap} lead to a lower plasma kinetic energy and even to a lower average density. Therefore, less energy has to be dissipated at the capillary walls. Similarly, for a given capillary radius, a larger laser waist yields in a reduced plasma kinetic energy.

Hybrid guiding scheme

Step I: Generation of a initial plasma state

Reflections at the capillary wall guide a first laser pulse at moderate intensity $I \approx 10^{16} - 10^{17}\ ^{W}/_{cm^2}$, ionizing the gas ($H_2$ or He) inside the tube.

Step II: Hydrodynamic expansion of plasma (as a result plasma channel is created)

Thermal relaxation	Shock expansion of plasma
(Fully ionized plasma thermal relaxation)	(Plasma column with radial pressure gradient required)

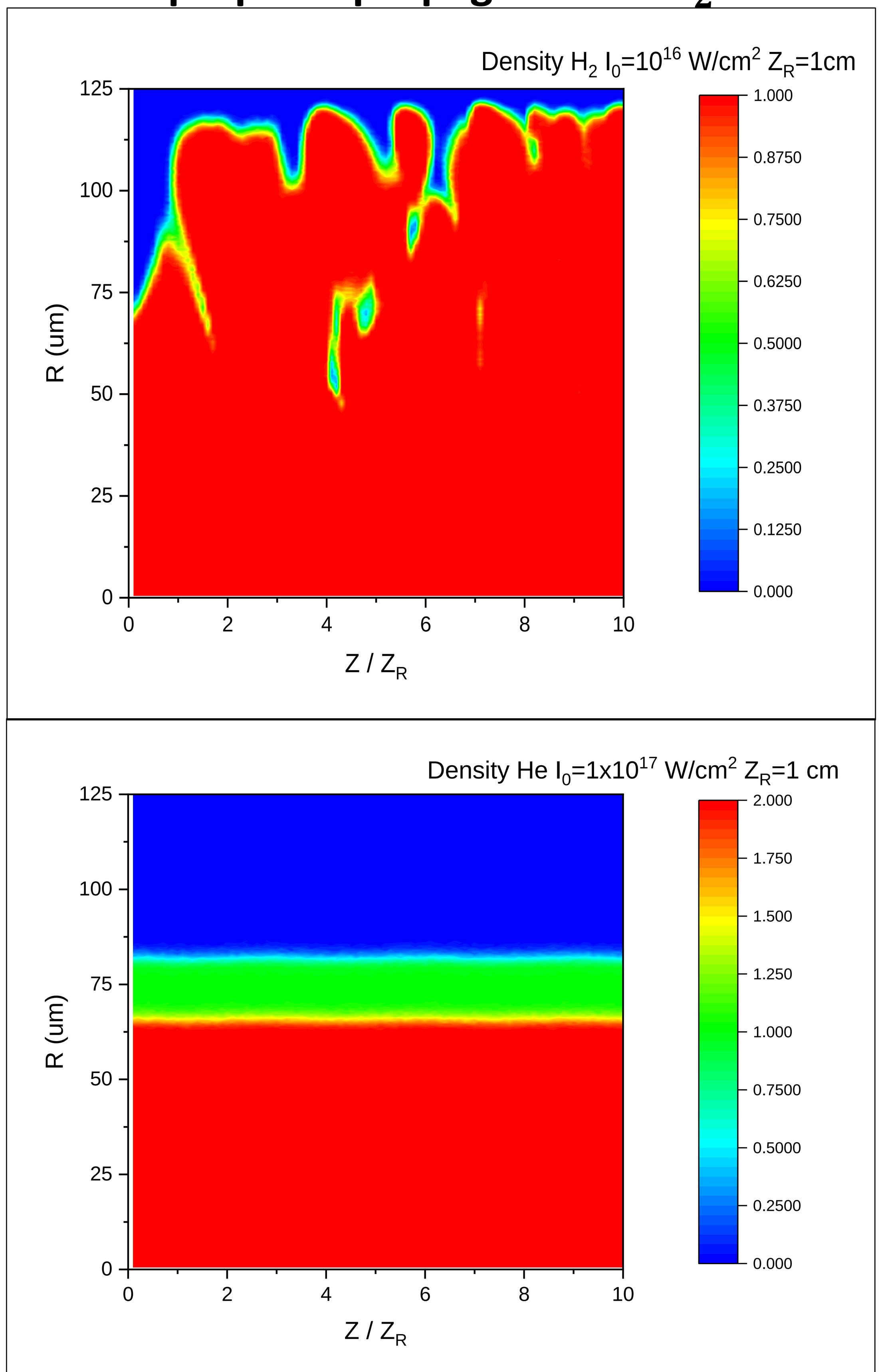
Step III: High intensity pulse guiding by plasma channel

First step: The laser of moderate intensity is guided by the index of refraction change from gas/plasma to wall under an angle close to grazing incidence.

Second step: plasma is expanding either as a shock wave in case of a plasma column (He case) or through thermal relaxation in case of full ionized tube (H_2) case. After some delay, the transverse density profile near the axis becomes parabolic : $n_e(r) = n_0\left(1 + \eta_{ch}\frac{r^2}{r_{ch}^2}\right)$, with $r_{ch} = Z_R\sqrt{n_e/n_c}$, n_c being the critical density

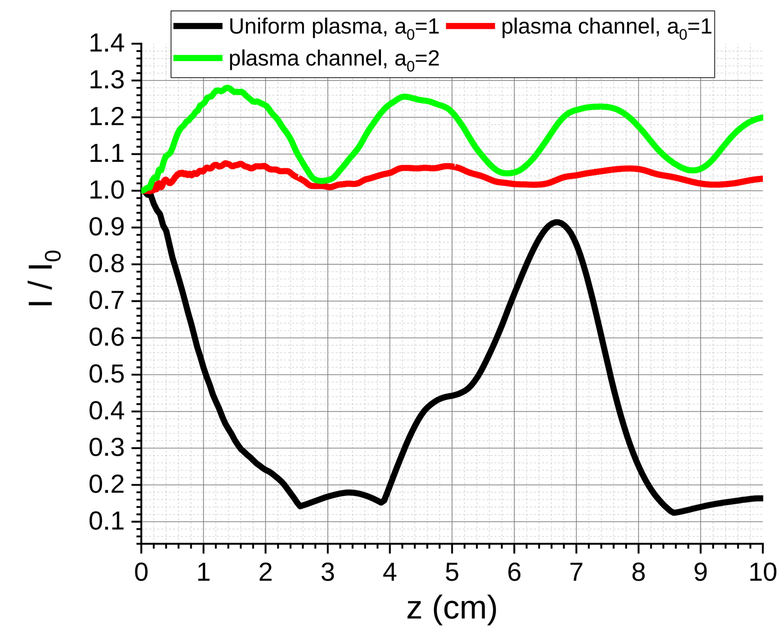
Third step: transverse variation of electron density changes the refractive index $\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega_L}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \varepsilon_0 \omega_L^2}$. In the best matching conditions $\eta \sim 1$, the high intensity laser $I \approx 2 - 5 \times 10^{18}\ ^{W}/_{cm^2}$ can be guided over large distances.

Laser prepulse propagation in H_2 and He



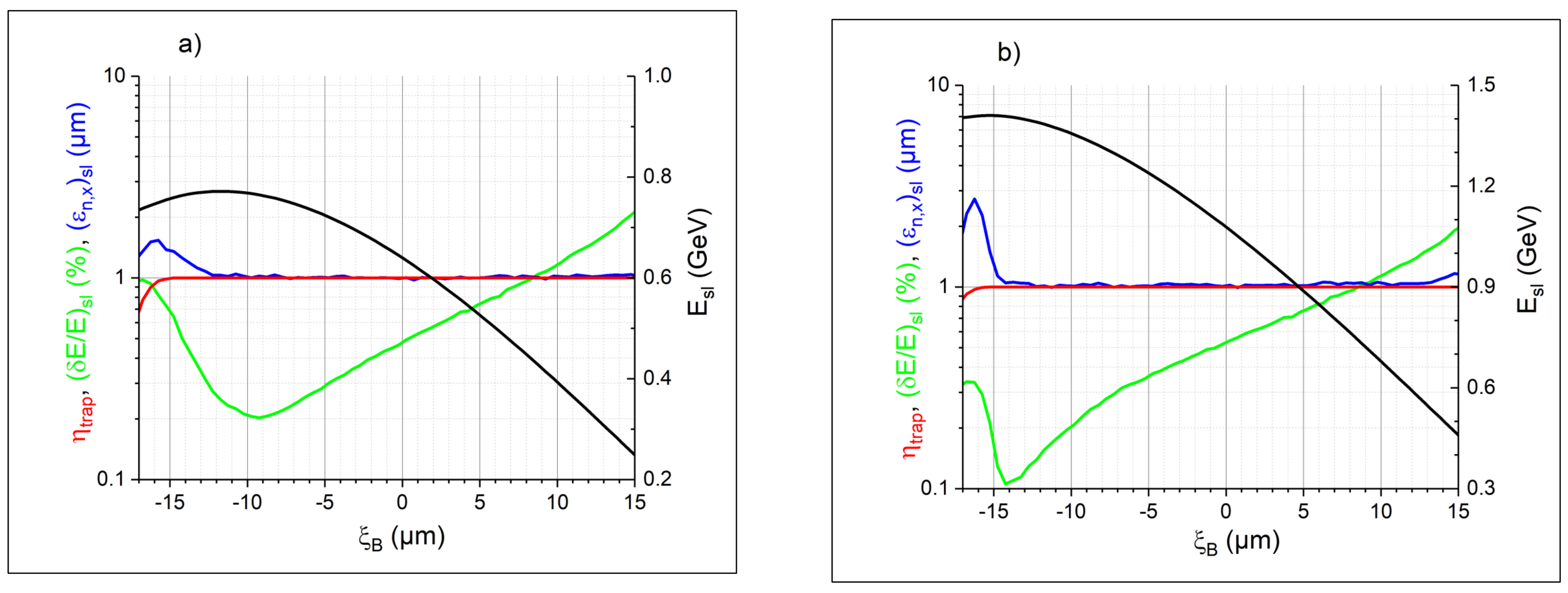
2D maps of electron density after interaction with the laser pre-pulse. Top figure: $gas = H_2$, $n_0 = 10^{17}\ cm^{-3}$, $R_{cap} = 125\mu m$, $I_0 = 10^{16}\ W/cm^2$. Bottom figure: $gas = He$, $n_0 = 10^{17}\ cm^{-3}$, $R_{cap} = 125\mu m$, $I_0 = 10^{17}\ W/cm^2$.

Propagation of the main pulse in plasma channel



Evolution of the maximum intensity on axis during propagation inside a capillary ($R_{cap} = 125\ \mu m$) with a plasma channel obeying best matched conditions for a laser waist of 50.5 µm. Nearly constant intensity on the axis is obtained in case of $a_0 \approx 1$. At higher laser intensities (a_0=2) relativistic self-focusing plays a significant role.

Electron beam properties after acceleration



Properties of the beam electrons at the exit of a 10 cm long capillary with $R_{cap} = 125mm$. The laser beam has a Gaussian radial profile with $w_L = 50.5$ µm and a_0=1. The electrons bunch is injected at 150 MeV, with a normalized phase emittance of 1 µm, and a transverse size of 2 µm. Left axis: ratio of trapped electrons η_{trap}, red line; slice dispersion in energy $(\delta E/E)_{sl}$, green line; slice normalized phase emittance $(\varepsilon_{n,x})_{sl}(\mu m)$, blue line. Right axis: slice average energy E_{sl}, black curve. Figure a) $\tau_{fwhm} = 45fs$, b) $\tau_{fwhm} = 132fs$

Configuration	$\mathcal{E}_L(J)$	$l_{cap}(mm)$	$\delta E/E$ (%)	$\langle(\delta E/E)_{sl}\rangle$ (%)	$\varepsilon_{n,x}(\mu m)$	$\langle(\varepsilon_{n,x})_{sl}\rangle(\mu m)$
$R_{cap} = 125\mu m$ $\tau_{fwhm} = 45fs$	4.1	142	1.2	0.1	0.75	0.73
$R_{cap} = 125\mu m$ $\tau_{fwhm} = 132fs$	12.0	76	0.6	0.1	0.74	0.74
$R_{cap} = 150\mu m$ $\tau_{fwhm} = 45fs$	4.1	142	1.2	0.1	0.74	0.73
$R_{cap} = 150\mu m$ $\tau_{fwhm} = 132fs$	12.0	76	0.6	0.1	0.74	0.73

Main properties of electron beam injected at 150 MeV and accelerated up to 1 GeV in the optimized configuration. Columns from left to right : laser energy in Joule, length of the capillary in mm, average of the total and slice dispersion in energy in percent and total and average of the slice normalized phase emittance in µm.

Conclusion

- A 1 GeV accelerator stage configuration for LPA have been proposed using an hybrid guiding scheme inside a capillary tube
- Main objective was to reduce the capillary tube radius in order to reduce the energy required to generate the plasma channel, and so to limit the damage on the capillary walls
- In order to limit diffraction effects at the entrance of the capillary, the laser electric field at the capillary walls must also be minimized.
- Our simulations results show that for the Gaussian laser to achieve such conditions capillary radius must be at least 2.5 times larger than the laser waist (e.g. $w_0 = 50.5\ \mu m, R_{cap} \approx 125\ \mu m$)

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